INJURY PATTERNS IN ROLLOVERS BY CRASH SEVERITY

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ABSTRACT

Earlier studies by the authors have proposed separating rollover crashes according to belt use, ejection status, and single vs. multiple harmful events. These different classifications were associated with differences that could substantially alter the risk of serious injury. For each classification, metrics to characterize rollover severity were presented. For most single vehicle crashes, the number of roof contacts with the ground was found to predict injury risk. For multi-harmful event crashes the extent of damage caused by the most severe non-rollover harmful event, combined with the number of roof impacts was found to predict injury risk.

This paper examines NASS/CDS 1995-2003 to determine the injury distribution by body region for the most frequently occurring rollover classifications that result in MAIS 3+ injuries from sources inside the vehicle. The examined classifications of rollovers include: belted not-ejected and unbelted not-ejected. For each category the injury patterns by body region were presented. Differences in injuries in near-side and far-side rollovers were evaluated.

In general, head injuries were the most frequent MAIS 3+ injury for belted occupants. However, trunk injuries were more frequent for belted occupants in near-side rollovers. It was found that a higher fraction of severe injuries occurred in far-side rollovers compared to near-side rollovers. This tendency held for rollovers with one roof impact or less as well as higher severity rollovers.

The frequency of injury and ejection for near and far-side rollovers was examined. The MAIS 3+ HARM distribution by body region was examined as a function of number of roof impacts and direction of roll for not ejected front seat occupants. About 46% of the occupants were exposed to far-side rollovers, but more than half of the injuries occurred in far-side rollovers.

To examine occupant kinematics in injury producing rollovers, a MADYMO 6.1 model of a front occupant compartment of a mid-size SUV with a belted Hybrid III dummy was used. The model was validated against an available staged test with a similar configuration.

Computer modeling suggest that a higher tripping acceleration results in higher roll rates which, in turn, can lead to increased number of roof impacts. Associated with the increase in roll rate was an increase in the maximum head velocity.

The data analysis and computer modeling suggest the need to assess the severity of the vehicle loading that causes the vehicle to rollover. The severity of the tripping forces may be related to the risk of injury.

INTRODUCTION

In an earlier study, crash factors that increased the risk of MAIS 3+ injuries were examined (Digges 2003). That study used NASS/CDS 1995-2001 data. These years were selected because more detailed information on rollovers was recorded in the case files beginning in 1995. The added data included the number of roll quarter-turns up to 16 and a category for end-over-end rollovers. Prior to 1995, the number of quarter- turns beyond four was not measured or recorded. The post 1995 NASS/CDS also recorded the extent of damage from planar crashes that may have occurred prior to or during the rollover. These added variables permitted a more robust examination of how planar damage and number of quarter-turns may influence the risk of injury. The earlier study found that the number of times the vehicle roof faces the ground was a statistically significant factor that predicted increased injury risk for single vehicle rollovers. For rollovers that were preceded by planar crashes, the combination of number of vehicle inversions and the extent of planar damage were predictors of injury risk. However, there was insufficient multiple impact data to obtain significance for this combination of predictors.

Many authors have found that ejection and partial ejection are outcomes that substantially increase injury risk. Countermeasures to reduce ejection casualties generally focus on preventing the ejection rather than preventing the injury after ejection occurs. Casualty reduction countermeasures for non-ejected occupants focus on preventing the injury. The safety features may be different for near-side rollovers than for far-side rollovers. Consequently, it is desirable to separate and study the injuries that occur to non-ejected occupants in rollovers and to examine both near-side and far-side injury patterns. The focus of this paper is to assess the injuries that occur to non-ejected occupants.

DATA QUERIES

The data set described in this paper was queried from The Crashworthiness Data System (CDS), a database of The National Automotive Sampling System (NASS), years 1995 through 2003. Definitions were prepared below for: occupant selection, rollover codification, crash configuration, restraint usage, rollover crash orientation, ejection status, injured body region groupings, injury severity, and occupant counts versus injury counts.

Occupant Selection

As described in previous works, occupancy rates of the various vehicle platforms dictated the selection of drivers. In order to remove bias and balance reporting, the right outboard passenger of the front seat, if present, was included.

Occupants were selected based upon seating position and age. The occupants of age 12 years and older were retained in this study. Occupants less than 12 years old were considered to lack biomechanical tolerance owing to their lack of osseous development and abundance of evolving soft tissue. This also accompanied the public safety mandate of placing children in rear seating positions until these occupants reached 12 years of age.

Quarter Turn Codification

Prior to 1995, rollover crashes were coded through the third quarter turn. Upon reaching the fourth quarter turn, one complete revolution, and above, these were grouped. Currently, the NASS CDS allows for discernment through the fourth complete revolution, 16 quarter turns. Rollover crashes of greater than 16 quarter turns have been grouped in the database.

In the current study rollover quarter turns have been grouped by roof impacts owing to the statistical significance of the relationship between the number of roof impacts and injury severity for restrained occupants, who comprise the majority of rollover occupants. Owing to similarities in the occupant outcomes for two roof impacts and three or more roof impacts, this category was aggregated into two plus roof impacts.

In addition to the classification of quantifiable quarter turns, rollover crashes may be defined as end-over-end rollover crashes or rollover with unknown details. The end-over-end rollover crash was excluded from consideration, within this context, owing to its severe nature and varying crash dynamics, from lateral rollover crashes. It was further reasoned that this type of rollover would merit an individual severity metric. The rollover of unknown detail was excluded since the number of quarter turns was not quantified and it could not be established whether the rollover was lateral or longitudinal.

Crash Configuration

Initially, an aggregate number of rollover crashes and characteristics were considered. Upon disaggregating this data, single and multiple vehicle impact rollover crashes were identified as having different injury characteristics, as well as vehicle crash dynamics.

Single vehicle crashes were disaggregated by object contacts. Those crashes involving fixed objects were identified as a separate severity metric. Further, the non-fixed object cases were identified as pure rollover cases.

Multiple vehicle crashes were disaggregated owing to their elevated occupant injury severity, approximately twice as high as in the single vehicle case.

Restraint Usage

Within the context of the rollover crashes, the concept of restraint usage was considered and modified from the traditional reporting. All of the manual and passive restraint systems, defined in NASS CDS, were considered in determining belted, ineffectively/inefficiently belted, and unbelted drivers.

The belted occupants were those whose restraint selection would potentially provide protection against

the forces imparted during a rollover crash. Those occupants protected by a lap belt, lap and shoulder belt combination, or a three point automatic belt were considered restrained for purposes of rollover.

The ineffective/inefficient restraint use category contemplated those occupants who were protected by something other than the previous category. These included certain elements of passive restraint use also. Ineffectively and/or inefficiently restrained occupants, with regard to rollover, were those using: shoulder belt, unknown belt type, other belt type, shoulder belt with child safety seat, lap belt used child safety seat, lap and shoulder belt with a child safety seat, unknown belt type with child safety seat, other belt type with child safety seat, unknown usage of belt, two point automatic belt, unknown type of automatic belt, and unknown availability but automatic belt in use.

The unbelted occupants did not benefit from any rollover mitigating active or passive restraint. The unrestrained group was comprised of any occupant not described in the restrained and ineffectively and/or inefficiently restrained categories.

Rollover Crash Orientation

Rollover crash orientation was based upon the seating position of the driver and rollover crash direction. The rollover crashes were categorized as far side or near side rollover crashes.
Rollover crashes with occupants seated on the left side of a right side leading rollover crash or occupants seated on the right side of a left side leading rollover crash were considered far side rollover crashes.

Rollover crashes with occupants seated on the right side of a right side leading rollover crash or occupants seated on the left side of a left side leading rollover crash were considered near side rollover crashes.

Ejection Status

The ejection status of an occupant was defined using the NASS CDS classification. These were: unejected, completely ejected, partially ejected, and ejection status unknown. Unejected occupants were those who remained within the vehicle during the crash. Completely ejected occupants were those who were expelled through an exit portal of the vehicle during the crash. Partially ejected occupants had some portion of their body stay within the vehicle while the remaining portion was exposed to the

exterior of the vehicle. Ejection degree unknown encompassed some form or amount of occupant expulsion for which the extent was not ascertainable. In this study, ejected occupants have been presented as an aggregate of completely and partially ejected or individually.

Injured Body Region Groupings

The NASS CDS was ultimately chosen owing to its very complete case definition. Not only were the crash, vehicle, and general occupant attributes available but also specific injury description by type and severity.

Using the AIS 90 classifications of The Association for the Advancement of Automotive Medicine (AAAM), a complete injury description was possible. Further, NASS CDS, when possible, related the injury to the crash mechanisms inherent to a specific crash. The body regions were defined as: head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity, and unspecified.

In this study, the body regions were collapsed into four major regions. The head was comprised of the head and face. The spine was comprised of the neck and spine. The trunk was comprised of thorax and abdomen. Finally, the extremities were comprised of the aggregate of upper and lower extremities. The injuries to unspecified body regions were excluded from this analysis.

Injury Severity

An injury severity scale, known as the Abbreviated Injury Scale (AIS), accompanied the AAAM injury classification. The AIS, defined as an ascending measure of the risk of mortality, associated each injury type, by injured body region, injury level, and injury aspect, to a severity level. AIS is defined as: zero (no injury), one (minor injury), two (moderate injury), three (serious injury), four (severe injury), five (critical injury), six (maximum injury), and seven (injury severity unknown). The classification of no injury was established to be used as a maximum injury definition, since uninjured body regions would not be listed.

In this study, serious injuries were of concern and the development of a metric that would assess increased severity with the increase of the measured quantity (roof impacts). Two groups were studied, those occupants sustaining maximum injury severity of three and greater and injury counts of AIS three injuries and greater. The first constituted an occupant

count, if this group had injuries detailed, these would include AIS one and two injuries. The second group constituted an injury count, which excluded AIS one and two injuries, if these existed.

A complete accounting of fatally injured occupants was absent when grouping the seriously injured occupants, sustaining MAIS 3+ injuries. Although AIS six injuries might result in fatality, the occupant treatment must be consulted in NASS CDS. Upon this indication of fatality, the occupant may be considered deceased as a result of the crash or by disease. Further, not all fatality injured occupants receive a maximum injury classification of six. In fact, a fatally injured occupant may have received an MAIS level as low as one or two. This case has been linked to a lack of medical records substantiating injuries and the NASS researchers and injury coders registering only documented injuries. A second method of classification of seriously injured occupants arose with MAIS 3+F occupants. These were occupants who sustained MAIS three through six injuries or fatally injured occupants with MAIS one or two injuries. For the injuries presented in this study the first method, MAIS 3+ injuries, was considered since the injuries were considered individually, as well as a group of seriously injured.

Occupant Counts versus Injury Counts

In reporting MAIS 3+ or MAIS 3+F occupants, the occupants have been reported once, where the occupants were specified. In the study of injury mechanisms, specifically, the present disaggregation, all injuries were included at any injury level. This was done to describe all injuries present at the various injury levels and rollover crash orientations.

For front seat occupants involved in near and far side rollover crashes with a quantifiable number of quarter turns, 389,423 were estimated to have sustained MAIS 3+ injuries. This was estimated from a raw sample of 5,239 occupants. Annualized estimates yielded 43,269 estimated occupants taken from 582 occupants over the nine years queried. Occupants classified with an other or unknown rollover crash orientation, end-over-end or some absent occupant parameter, numbered 13,015 (176 raw cases.) These were annualized and accounted for 1,446 (20 raw cases.)

INJURIES AND INJURY RATES FOR EJECTED AND NON-EJECTED OCCUPANTS

An overview of the NASS/CDS 1995-2003 injury data is shown in Tables 1 through 3.

Table 1 shows the number of belted and unbelted front seat occupants 12 years old and older by belt use and ejection status. Table 2 shows the associated number on MAIS 3+ injuries in each category. Table 3 shows the rate of MAIS 3+ injuries per 100 occupants exposed to each of the cells in the Table 1 matrix.

Table 1.
Rollover Exposed Front Seat Occupants by Belt Use and Ejection Status

OCCUPANTS	Belted	Unbelted
NO EJECTION	1,958,515	577,096
COMP. EJECT	4,113	102,357
PART EJECT	44,688	35,815
EJECT DEG UNK	545	3,413
TOTAL	2,007,861	718,681

Table 2.
MAIS 3+ Injured Front Seat Occupants by Belt Use and Ejection Status

MAIS 3+	Belted	Unbelted
NO EJECTION	23,373	23,644
COMP. EJECT	397	26,450
PART EJECT	2,121	3,454
EJECT DEG UNK	0	654
TOTAL	25,891	54,202

Table 3.
MAIS 3+ Injured per 100 Front Seat Occupants Exposed by Belt Use and Ejection Status

MAIS3+/100	Belted	Unbelted
NO EJECTION	1.2	4.1
COMP. EJECT	9.6	25.8
PART EJECT	4.7	9.6
EJECT DEG UNK	0.0	19.2
ALL	1.3	7.5

It is of interest to know how the populations in Tables 1 and 2 divide between near-side and far-side rollover crash exposure. Table 4 shows the percentage of the belted populations that are in far-side crashes. In the table complete and partial ejections have been combined. Table 5 shows similar data for the unbelted populations.

It may be noted in Tables 1 and 4 that of the 48,801 occupants that were totally and partially ejected belted occupants, 34.9% were in far-side rollovers. However, 64.7% of the MAIS3+ injuries among belted ejected occupants were in far-side rollovers.

Fortunately, this injured population is small. It comprises 10% of MAIS 3+ injuries to belted occupants in rollovers, and 3% of combined belted and unbelted MAIS 3+ injuries.

Table 4.
Percent of Belted Occupants In Far-side Rollovers and Percent Of Belted MAIS 3+ Injured Occupants In Far-side Rollovers by Ejection Status

BELTED FAR-SIDE	Occupants	MAIS 3+
NO EJECTION	46.3%	50.4%
ALL EJECTION	34.9%	64.7%
TOTAL	46.0%	51.8%

Table 5.
Percent of Unbelted Occupants In Far-side Rollovers and Percent Of Unbelted MAIS 3+ Injured Occupants In Far-side Rollovers by Ejection Status

UNBELTED FAR-SIDE	Occupants	MAIS 3+
NO EJECTION	46.5%	65.6%
ALL EJECTION	50.0%	47.4%
TOTAL	47.2%	55.2%

INJURIES BY BODY REGION

In examining injuries by body region, we include all injuries to an occupant. The previous data used the MAIS scale, which considered only the most severe injury. In rollover crashes, occupants frequently sustain multiple injuries. Sometimes there are multiple injuries to the same body region and even to the same organ. Accounting for multiple injuries to the same body region presents challenges in how best to minimize biases. A variety of methods have been used, but there is no generally accepted procedure. The data to follow includes all injuries, including multiple injuries to the same body region or organ.

Tables 6 and 7 display the number of injuries by AIS and body region for belted and unbelted front seat occupants that are not partially or completely ejected.

Table 8 summarizes the AIS 3+ HARM to belted and unbelted not ejected occupants and shows the percentage distribution by body region. AIS 3+ HARM is calculated by applying the injury cost weighting factor to each category of AIS injuries. The weighting factors are from NHTSA (NHTSA 2001). The units of HARM units are equivalent fatalities. The relevant occupants are front seat not ejected occupants age 12 and older.

Table 6.
Injuries to Belted Not Ejected Relevant Occupants by Body Region and AIS

BELTED NOT EJECT	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6	AIS Unk	Total
HEAD	843,413	72,741	12,249	7,897	2,347	320	771	939,739
SPINE	456,396	22,633	8,484	623	860	175	235	489,405
TRUNK	273,014	29,104	26,570	4,051	853	190	2,727	336,509
EXTREM	1,479,526	76,502	22,000	0	0	0	152	1,578,178
UNSPEC	38,409	48	476	119	0	1,104	0	40,155
TOTAL	3,090,756	201,027	69,778	12,690	4,060	1,790	3,885	3,383,987

Table 7.
Injuries to Unbelted Not Ejected Relevant Occupants by Body Region and AIS

UNBELTED NOT EJECT	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6	AIS Unk	Total
HEAD	452,922	80,568	18,767	15,732	5,133	230	2,710	576,062
SPINE	110,928	24,784	9,137	346	823	184	0	146,201
TRUNK	123,911	11,617	16,997	5,491	2,009	312	1,341	161,678
EXTREM	484,041	49,721	20,860	13	0	0	359	554,993
UNSPEC	43,086	82	102	0	1,106	291	0	44,668
TOTAL	1,214,889	166,771	65,864	21,582	9,071	1,017	4,409	1,483,601

Table 8.
AIS 3+ HARM and Percentages for Belted and Unbelted Not Ejected Relevant Occupants by Body Region

Body Region	Belted HARM	Belted % HARM	Unbelted HARM	Unbelted % HARM
HEAD	5,898	35%	11,058	49%
SPINE	2,083	12%	2,064	9%
TRUNK	5,172	30%	5,521	25%
EXTREMITY	2,622	15%	2,490	11%
UNSPECIFIED	1,193	7%	1,241	6%
TOTAL	16,968		22,375	

NEAR AND FAR SIDE INJURIES BY BODY REGION

Earlier research reported a higher risk for occupants in far-side rollovers as compared to near-side rollovers (Parenteau 2001). A further investigation of roll direction difference is merited.

Table 9 shows the distribution of AIS 3+ HARM for not ejected belted front seat occupants by direction of rollover. The percentage of injuries that occur in far-side rollovers is shown for each body region. Table 10 shows similar data for unbelted not ejected front seat occupants.

Table 9.
AIS 3+ HARM for Belted Not Ejected Relevant Occupants by Body Region in Near and Far Side Rollovers and Percentage of AIS 3+ HARM in Far-side Rollovers

Belted Body Region	Near	Far	% Far
HEAD	2,192	3,706	63%
SPINE	626	1,458	70%
TRUNK	2,726	2,446	47%
EXTREM	1,228	1,394	53%
UNSPEC	1,193	0	0%
Total	7,965	9,003	53%

INJURIES BY NUMBER OF VEHICLE ROOF IMPACTS

Earlier studies by the authors found that a crash severity measurement for rollovers is the number of times the roof has the opportunity to face the ground (Digges 2003). During the quarter turn that the roof faces the ground, no impact may occur or multiple impacts may occur. For accounting convenience, any of the above are classified as one roof impact with regard to the severity metric.

Table 10.
AIS 3+ HARM for Unbelted Not Ejected Relevant Occupants by Body Region in Near and Far Side Rollovers and Percentage of AIS 3+ HARM in Far-side Rollovers

Unbelted Body Region	Near	Far	% Far
HEAD	2,877	8,181	74%
SPINE	613	1,452	70%
TRUNK	2,045	3,476	63%
EXTREM	1,099	1,391	56%
UNSPEC	235	1,006	81%
Total	6,869	15,506	69%

Tables 11 and 12 show the distribution of AIS 3+ injuries by body region by number of roof impacts for belted and unbelted, respectively. The 2+ roof impacts category includes all number of quarter-turns greater than 5. The 1 category is for all quarter-turns less than 6. One quarter-turn was included in the 1 category for convenience and because of small numbers.

Table 11.
AIS 3+ HARM for Belted Not Ejected Relevant Occupants by Body Region and Number of Roof Impacts

Belted Body Region	Roof Impacts 1	2+
HEAD	28.6%	6.1%
SPINE	10.3%	2.0%
TRUNK	19.4%	11.1%
EXTREM	11.7%	3.7%
UNSPEC	6.8%	0.2%
TOTAL	76.8%	23.2%

Table 12.
AIS 3+ HARM for Unbelted Not Ejected Relevant Occupants by Body Region and Number of Roof Impacts

Unbelted	Roof Impacts	
Body Region	1	2+
HEAD	46.0%	3.4%
SPINE	8.4%	0.9%
TRUNK	23.1%	1.6%
EXTREM	10.3%	0.8%
UNSPEC	5.5%	0.0%
TOTAL	93.4%	6.6%

INJURIES BY ROLL DIRECTION AND NUMBER OF VEHICLE ROOF IMPACTS

Tables 13 and 14 present the percentage of the AIS 3+ HARM from Tables 11 and 12 that are in far-side rollovers.

Table 13.
Percent of AIS 3+ HARM for Belted Not Ejected Relevant Occupants That Occur in Far-side Rollovers by Body Region and Number of Roof Impacts

Belted Far-side	Roof Impacts	
Body Region	1	2+
HEAD	64%	56%
SPINE	67%	88%
TRUNK	64%	18%
EXTREM	49%	68%
TOTAL	56%	42%

Table 14.
Percent of AIS 3+ HARM for Unbelted Not Ejected Relevant Occupants That Occur in Far-side Rollovers by Body Region and Number of Roof Impacts

Unbelted Far-side	Roof Impacts	
Body Region	1	2+
HEAD	74%	71%
SPINE	69%	80%
TRUNK	64%	55%
EXTREM	54%	77%
TOTAL	69%	69%

SIMULATIONS OF NEAR AND FAR ROLLOVERS

A rollover crash can generally be divided into three phases – tripping, airborne, and ground contact. Some rollovers may repeat the airborne and ground contact phases more than once. Injuries may occur during any of these phases. The occupant kinematics will vary depending on belt use and roll direction relative to the occupant. Consequently, the roll direction may also influence injury outcome.

To better understand the occupant kinematics in near-side and far-side rollovers, computer modeling of rollovers was conducted (Burel 2003, Dahdah, 2005). The baseline acceleration for the model was from an actual vehicle rollover test. The test was of an SUV exposed to an 18 mph tripping acceleration pulse. The roll was induced by an impact with a curb as the vehicle slid sideways. The lateral acceleration reached a maximum of 12 G about 15 ms after impact with the curb. After about 24 ms the acceleration reversed signs. It again reached about 6 G between 150 and 200 ms. The initial acceleration pulse lasted about 24 ms and was due to the curb impact; the subsequent acceleration was both lateral and vertical. It was produced by the release of energy from the suspension system. The tripping acceleration induced a roll rate of about 270 deg/sec. To evaluate variations in the tripping pulse, the baseline pulse was scaled using the same time duration, but proportionally increasing or decreasing the acceleration. Tripping pulses on 5, 10, 15, 20, and 25 mph were simulated for near-side and far-side rollovers. The roll rates that resulted from these pulses are shown in Table 15.

Table 15.
Roll Rates that Resulted from Modeling the Tripping Pulse

Trip Velocity mph	Roll Rate Deg/Sec
5	70
10	150
15	230
20	310
25	380

An initial difference noted between the near-side and far-side rollovers was that the role of the safety belt differs. For far-side rollovers, the seat rises under the occupant and the lap belt is temporarily unloaded. In near-side rollovers, the seat falls away from the occupant after the initial launch of the vehicle has

ended. In addition, interaction with the door can restrict the lateral motion of the occupant.

The modeling indicated that the occupant's maximum head velocity increased with the severity of the tripping pulse and the resulting roll rate that it induced. The results are shown in Table 16.

Table 16.
Maximum Head Velocities Resulted from Modeling Tripping Pulses of Different Severity by Roll Direction

Trip Velocity mph	Max Head Velocity m/sec	
	Near-side	Far-side
5	1.65	0.55
10	3.70	1.38
15	4.17	3.29
20	4.20	4.69
25	4.25	5.73

Maximum belt loads and head excursion were also found to increase with increased severity crash pulse. These results suggest that the tripping pulse could be another indicator of rollover crash severity.

CONCLUSIONS

This study investigated injuries to front seat occupants 12 years and older in near-side and far-side rollovers. The study excludes cases in which the belt use was unknown or the belt was improper for rollover protection. End-over-end rollovers were also excluded. All completely and partially ejected occupants were excluded from the analysis of injuries by body region.

The examination of ejections and partial ejections in the relevant population showed that 55% of the unbelted occupants with MAIS 3+ injuries were ejected. This compared with 9.5% for the belted population. Most unbelted injuries are from complete ejections, comprising 88% of the combined complete and partial ejections. In contrast 84% of belted ejections are partial ejections.

The relevant belted and unbelted populations were exposed to near-side rollovers slightly more frequently than far-side rollovers. However, the number of occupants with MAIS 3+ injuries was greater for both belted and unbelted populations in far-side rollovers. The relevant population of unbelted occupants was ejected about equally in near-side and far-side rollovers. Far-side partial ejections

for belted occupants were much less frequent than near-side partial ejections, but when they occurred they were more likely to produce serious injuries.
An examination of the AIS 3+ HARM by body region shows that for belted and unbelted not ejected occupants, head injuries are the largest fraction at 35% and 49%, respectively. Trunk injuries comprised 30% of the belted HARM and 25% of the unbelted HARM.

An examination of AIS 3+ HARM by roll direction indicates that far-side rollovers consistently produce the largest fraction for unbelted not ejected occupants. Over 70% of the head and spine HARM for this unbelted population is in far-side rollovers. For belted not ejected occupants, the HARM was more evenly split between near and far-side rollovers. Trunk injuries were more frequent in near-side rollovers but all other body regions were at higher risk in far-side rollovers.

The distribution of AIS 3+ HARM by the number of roof impacts shows a very large difference between belted and unbelted. For the belted, 38% of the AIS 3 + injuries and 23% of the AIS 3+ HARM occurs in rollovers with more than one roof impact. This compares with only 6.6% of the HARM for the unbelted. Previous studies have shown that the ejection risk increases with number of roof impacts. Consequently, the number of injuries in multiple roof impacts is much higher when the complete unbelted population is considered.

Countermeasures to reduce rollover injuries to the belted population need to consider protection in rollovers with more than one roof impact because 34% of the AIS 3+ injuries and 23% of the AIS 3+ HARM to the relevant belted population occur in these crashes. More than half of AIS 3+ HARM to relevant belted occupants occurs in far-side rollovers.

Modeling of rollover events indicates that the severity of the tripping pulse is an indicator of rollover crash severity. There is a need to collect crash data on measurements that would allow the prediction of the severity of the tripping pulse.

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